Memorandum

To: David Willy and Karin Wadsack
From: Balance of System and Testing Team
Date: 4/18/2014
Re: Project Proposal

Professor David Willy and Karin Wadsack, the balance of system and testing team is proud to convey the final design and expected cost for the selected components that fall under the Balance of System and Testing Team's obligations. The components to be made by the team include the base, tower, yawing system, main frame and nacelle. The base will be constructed of 16 gauge steel to maintain portability while still being strong enough, the final cost is $38.39 for materials and $180 for manufacturing. The tower will be constructed out of 6061 aluminum alloy piping and be a monopole design. The cost of the tower will be $412.00 and cost $45.00 to manufacture. The yawing system will be a passive yaw, two ball bearing system and will cost $133 for parts and $112.50 for manufacturing. Similarly to the base, the main frame will be made from 16 gauge steel. The material cost for these two components will be $1.50 with it costing $22.50 to manufacture. To streamline the design, the nacelle with an integrated faired tower section was implemented and will cost $100.00 to create and will be outsourced to another company for manufacturing. All of the spoken for components will cost $1067 for the production units and $380 for the initial prototype. Testing facilities for the prototype have been graciously donated for the project. The individual component selection and cost will be further discussed in the attached report.

DOE Wind Turbine

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Final Report

Document

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Abstract

The DOE Wind Turbine is based around a Collegiate Wind Competition by the Department of Energy. In order to compete, a micro wind turbine must be designed and manufactured in order to generate power for small electronics and to meet the requirements designated by a business plan. The wind turbine will then compete for points by means of testing in several different scenarios. The major client, for this project, consists of two professors with the US Department of Energy as the secondary client.

From the business plan, it was determined that the turbine will be sold in post disaster areas. Usually after a disaster occurs, electricity is not available and having to transport fuel is considered an extreme inconvenience and a hassle. By using renewable energy, the need for fuels will be reduced. The turbine will then need to be designed for portability so it can easily be transported to disaster affected locations, even in the case of road obstructions. From these constraints, the project goal became to develop a small wind turbine used to charge small electronics for use in post disaster scenarios.

This particular team was in charge of all non-electrical components for the wind turbine except for the blades, hub design, and gearbox. Six essential components were selected for individual discussion: the tower, base, yawing system, main frame, and nacelle. The tower and base are designed to stabilize and support the turbine in areas where wind will be more readily available. The yawing system allows the turbine to freely rotate 360° for the purpose of directing the blades into the wind. The main frame acts as the main structure of the turbine and contains the generator and gearbox. The nacelle covers all the components on the main frame and protects them from environmental exposure. The nacelle also is combined with a faired tower section that protects the yawing system and helps reduce turbulent airflow into the blades and blade fatigue from the tower.

For each component, three main options were designed and analyzed. Buckling and bending analyses were conducted on the tower to define the diameter needed and the base and main frame were analyzed to determine the material and thickness needed. Analysis was also done on the yawing system, which resulted in the selection of two deep-groove ball bearings to be used on the yaw shaft.

Complete system testing was conducted in a wind tunnel to verify that the cut-in wind speed, rated power, and blade rotor speed matched specifications of the business plan. In addition, testing was done to compare the differences in performance for a downwind turbine equipped with a nacelle and that of a turbine without a nacelle.

Cost analysis was done on the final design, breaking down the expected material cost and the manufacturing cost for each component. The final production cost was calculated from the total material and manufacturing. A prototype cost is also shown, that has the expected cost for building the turbine, assuming the team will do all the manufacturing on their own with some material will be donated.

Chapter 1. Introduction

1.0 Project Overview

The United States Department of Energy (DOE) has developed the Inaugural Collegiate Wind Competition for May 2014. During this competition, a number of approved colleges from around the country will present a business plan and small scale wind turbine both made to satisfy a need of each team's choice. Northern Arizona University (NAU) staff members, Karin Wadsack: Lead Professional Investigator, David Willy: Faculty Advisor, and the Department of Energy (DOE): Secondary Advisor, are acting as a bridge for the NAU team on behalf of the competition in order to help the university make an impression on a national scale and support renewable energy.

1.1 State of the Art Research Summary

For downwind turbines, a greater blade fatigue loading is seen due to the turbulence being caused by the wind flowing over the cylindrical tower and separating, as compared to an upwind turbine with similar blades [1]. According to tests done, having a tapered, or faired, tower section upwind of the blades in a downwind turbine, blade fatigue loading can be decreased by up to 8% in blade root bending. In addition, the use of a faired tower section reduces 28% of the tower bottom moment [2].

Vibrations can be damaging to a mechanical system and it is important to mitigate their effects. The vibration suppression controller analyzed in “Suppression of the vibrations of wind turbine towers” used torque with collocated feedback from the velocity or angular velocity of a nacelle turbine to increase stability. This design can be used to decrease vibrations in turbine towers [3].

The team is considering using steel or aluminum for the tower design. Wind turbine towers are most commonly made out of steel. The “Wind Turbine Materials and Components” chapter of the Wind Energy Explained textbook gives an overview of turbine tower design. The tower of a turbine is often made of cast steel and set in a reinforced concrete base. Wind turbines can also be installed in deep holes drilled into rocky surfaces, these are often structurally reinforced with concrete [4]. As concrete is not easily portable, the team has decided that it is a poor choice for our base.

Looking at “Five of the Best Micro Wind Turbines” helps give an idea of the competitors that exist in the small wind industry, which include the SkyStream, the Air X, and the Whisper all from Southwest Wind Power, AeroVironment's Architectural Wind, and the Excel by Bergey. The cheapest and smallest of these turbines is the Air X, with a cost of $600 and a power output of 38 kilowatt-hours per month, which relates the most to this design out of all five of these choices [5].

“101 Small Wind Turbines” gives a basic explanation of the factors and components that go into small wind turbines, and how system designs are made using those decisions. For example, in a densely populated area, the height required to obtain a certain wind speed increases when compared to an unobstructed area. Also, upwind turbines require a tail or some other corrective system to yaw into the wind, and that downwind systems do not. The decision between a truss and monopole tower, as well as that of the shape and flexibility of the turbine blades, are basically outlined [6].

When designing the turbine, the yawing system was an important aspect. Of current designs were researched for small wind turbines, three simple options were selected. [8] To understand the slip ring that will be used transfer the power from the rotating portion to a stationary portion. The reliability was researched for the slip rings to make sure that it will not default. [9]

Since the initial designs were to use guy wires, research was done to find suitable techniques for the use of guy wires. One of the developments in guy wire utilization found was using an insulating protective cover sleeve on the guy wires. For the sleeve "the lower end portion of the sleeve is secured a clamp, likewise of insulating material"

Chapter 2. Problem Formulation

2.1 Project Problem and Need

Since the need is dependent on each university's team, the NAU team searched for a niche market for small scale wind power. The Business sub-team determined a need for an alternative energy source using a renewable resource during post disaster scenarios where fuel may be difficult to obtain. In order to satisfy this need, the NAU team's project goal is to develop a small wind turbine which is used to power small electronics for use in post disaster scenarios.

2.2 Project Objectives

In order to satisfy the team's project goal, the Balance of Systems and Testing sub-team developed a number of objectives to accomplish, as described in **Table 1-1**.

Table 1-1: Summary of Objectives

Objective	Measurement Basis	Units
Maximum of three people needed to assemble	Ease of construction	Man Hours
Inexpensive	Cost to construct a single turbine	Dollars
Power output	Power produced	Watts
Lightweight	Overall turbine weight and portability	Kg
Small size	Amount of space the turbine takes up when assembled/disassembled	m^3
Reliable	How long the turbine will function	Years
Durable tower	Tower strength	MPa
Ability to yaw into the wind	Ability to face the wind	Degrees

In order to accomplish these objectives, the turbine will be tested in a wind tunnel specified by the competition. In this environment, the turbine will be evaluated by its ability to:

- Generate power within wind speeds of 5 m/s to 14 m/s
- Withstand a fluctuating wind speed up to 17 m/s
- The blades must come to a complete stop within 10% of the system's rated rotor speed or come to a complete stop within 10 seconds
- Must produce power when loaded with a continuous 5-volt load

2.3 Operating Environment

For this project there are two designated operating environments. The first operating environment is based off of where the wind turbine is going to be tested and the second operating environment is determined by the market constraints. The operating environment based on testing at the competition specified wind tunnel which is used for the following criteria:

- Produce power over wind speeds from 5 m/s to 14 m/s
- Withstand wind speeds exceeding 17 m/s
- Check stopping ability of rotor while turbine is operational

Where the operation environment based on the determined market which is evaluated using the following:

- Used in Midwest United States Territories
- Operates within temperature ranges from 0°C to 50°C

2.4 Constraints

The turbine design is to fit two different constrained, one by the DOE Competition that constrains functionality, size, and ability to test, and one based off the business plan that is for how the turbine will be used. The following constrains are given by the competition and business plan requirements:

Competition

- Turbine must produce a minimum of 10 W to power small electronics
- Rotor must fit within a 45cm x 45cm x 45cm area
- Must use Department of Energy (DOE) provided generator
    - Great Planes Ammo GPMG 5225
- Must be able to withstand fluctuating wind speeds up to 17m/s
- Minimum tower height of 10ft
- Rotor must be able to brake within 10% of rated rotor speed

Business Plan

- Must be able to be used in multiple different terrains for post-disaster scenarios
- Must be portable to transport and set up quickly for emergency power supply
- Carried and constructed by 3 to 4 people
- Constructed in under 2 hours

[10]. The purpose of using the sleeves to cover the guy wires is to protect the guy wires from the environment it's operating in. Since the turbine that is being developed has to operate in a variety of environments, it could be beneficial to use cover sleeves to maintain the integrity of the guy wires used.

ASME standards are used for the wind tunnel testing that was done this semester as it is the most useful standard for these applications. [11]

2.6 Quality Function Deployment (QFD)

The Quality Function Deployment (QFD) summary in **Table 2-1**, displays the customer needs weighted by importance, with ten being the most important design aspect and one being the least, in relation to the engineering objectives. Based on what was decided, the most important design aspects were as follows:

- The turbine be durable
- Charge small electronics
- Fit within the competition testing constraints.

Looking at effects on the customer needs based off of the engineering requirements, there were four requirements determined to be most important and are as follows:

- Size of the turbine, which directly affects the storability
- Portability, and ease of turbine construction
- Ability to yaw into the wind, which influences the amount of power the turbine is able to produce;
- Turbine reliability, for the design's market needs.

The requirement that was determined with the lowest importance rating was inexpensiveness of the design, largely because the customer needs associated with the Balance of System and Testing sub team were not highly reliant on cost.

Table 2-1: Quality Function Development Summary.

Customer Needs	**Weights**	Maximum of 3 people to assemble	Inexpensive	Power Output	Lightweight	Small size	Reliability	Durable tower	Ability to yaw into the wind
Cost effective	6		9		6	6	3	3	6
Safety	9						3	6	
Storable	8	1			3	9			6
Portable	9	6			9	9			
Durable	10		6				9	9	1
Fits within testing constraints	10					9			3
Easily	9	9			3	1			

constructed									
Operates in low wind speeds	5			6			3		9
Consistently faces into the wind	8			6					9
Charges small electronics	10			9			9		3
Units		People	Dollars	Watts	kg	m³	Years	MPa	Degrees
Total		**143**	**114**	**168**	**168**	**288**	**240**	**162**	**271**

Chapter 3. Proposed Design

3.0 Proposed Design

3.1 Base

The base is the main structure that supports the tower and turbine. It also acts as a means for storing all of the electrical controls, battery, and any additional supplies.

3.1.1 Design

The base has been constructed from 16 gauge sheet metal and has a footprint of roughly 20 inches by 18 inches with a height of 9 inches. There are four holes on the base plates to allow for anchors to be driven into the ground to stabilize the base while the tower is being raised. A hole was placed in the two vertical sections of the base to allow a 3/4” bolt to be placed through the holes to act as a pivot point when raising the tower. The base has also been painted with a cold-galvanizing compound to prevent corrosion. The turbine base can be seen in Error! Reference source not found.**3-1**. A shelf was placed on the base where a weatherproof enclosure sits and contains the electrical components. This structure also acts as a convenient place for the user to place their electronics while they are being charged.

Figure 3-1: Finished Base Design

3.1.2 Analysis

To ensure that the material of the base would be sufficient to withstand the forces it was exposed to, analysis was done on the assembled base design in SolidWorks. The individual components of the base were made out of 16 gauge metal in SolidWorks and were assembled as a single assembly using welds. The main force that the base must withstand takes place at the pivot point on the base where the tower bolts to the base. Therefore, the force exerted by the tower under operating conditions was placed there to analyze the Von Mises stress and the displacement. From the FEA analysis it can be seen that the greatest Von Mises stress is 2.24MPa (**Figure 3-2**) and the greatest deflection is

$1.82x10^{-2}$mm (**Figure 3-2**). From this data, it was found that 16 gauge sheet metal was sufficient for the design of the base.

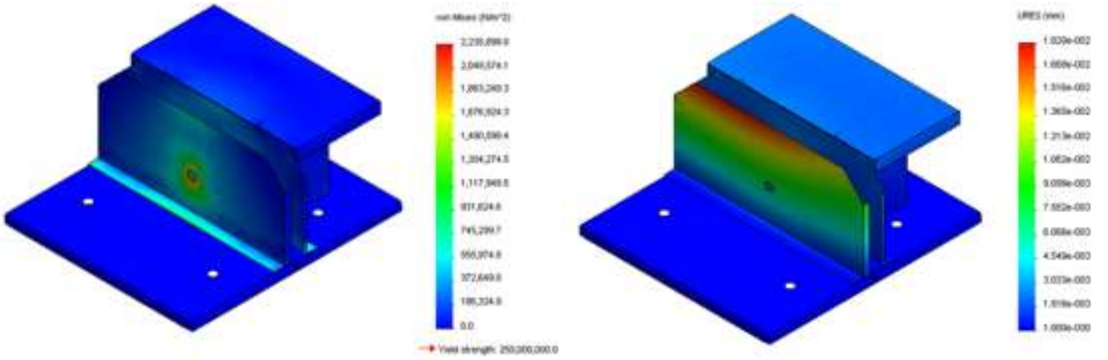

Figure 3-2: Base Von-Mises Stress Analysis and base deflection Analysis

3.2 Tower

The tower is the main structure used for erecting the turbine into the air in order to reach better wind regimes.

3.2.1 Design

Figure 3-3: Guy Wire Fixture

The turbine tower consists of three 6 ft. long threaded 6061 aluminum alloy sections and a single 3 ft. section at the top of the tower. Each section is held together with a threaded fitting with the exception of the first and final sections. The first section, located at the base of the tower, is held in place with a bolt, which securely fixes it to the base and allows the tower to rotate. The tower rotation allows the tower to be erected simply, while the base remains fixed. The final section, located at the top of the tower, has a threaded plug press fit into the top where the yaw shaft threads into the tower. The assembled tower is approximately 21 ft. tall. A guy wire fixture sits on the final tower couple and can be seen in Error! Reference source not found.**3-3**. This fixture is where the guy wires are attached to the tower and is angled at the ideal guy wire angle of 60^0 with respect to the ground. A cold-galvanizing compound covers the guy wire fixture to prevent corrosion. The actual guy wires are made of 1 x 7, 1/16” stainless steel wire rope.

3.2.2 Analysis

Analysis initially completed on the tower showed that the tower exhibited fairly large deflections at the desired height and diameter. To minimize deflection, guy wires are used to stabilize the tower. In order to determine the optimal position to reduce buckling deflections, the resultant tension force was placed at a series of heights initially aligning with tower segment, or 6ft (1.83m), increments. This analysis found that the ideal guy wire location was at 18ft (5.49m).

While further analyzing guy wires, tension was calculated on one guy wire that had to oppose a straight-on force. The schematic, shown in **Figure 22**, was drawn with a 21 foot tower in mind, with the guy wires at 18 feet up and a 60 degree angle between the flat ground and attachment point on the wire. With that in mind, the guy wire is to be anchored 8 feet from the tower with a length of 16 feet.

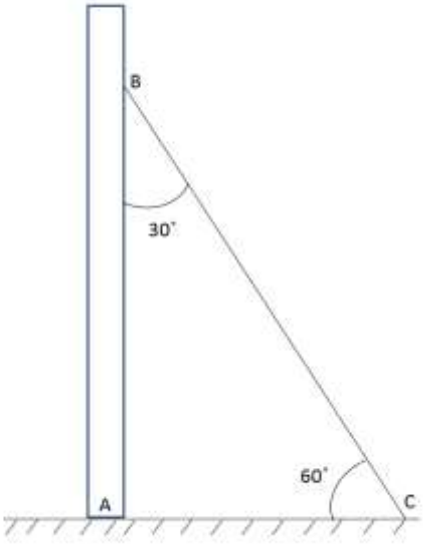

Figure 3-4: Guy Wire Schematic

Bending analysis was completed on the tower, assuming the highest stress scenario would be when the tower is raised with a maximum nacelle weight of 60N, shown in **Figure 3-4**. **Figure 3-5** shows the tower deflection due to a buckling stress from the weight of the components on the tower.

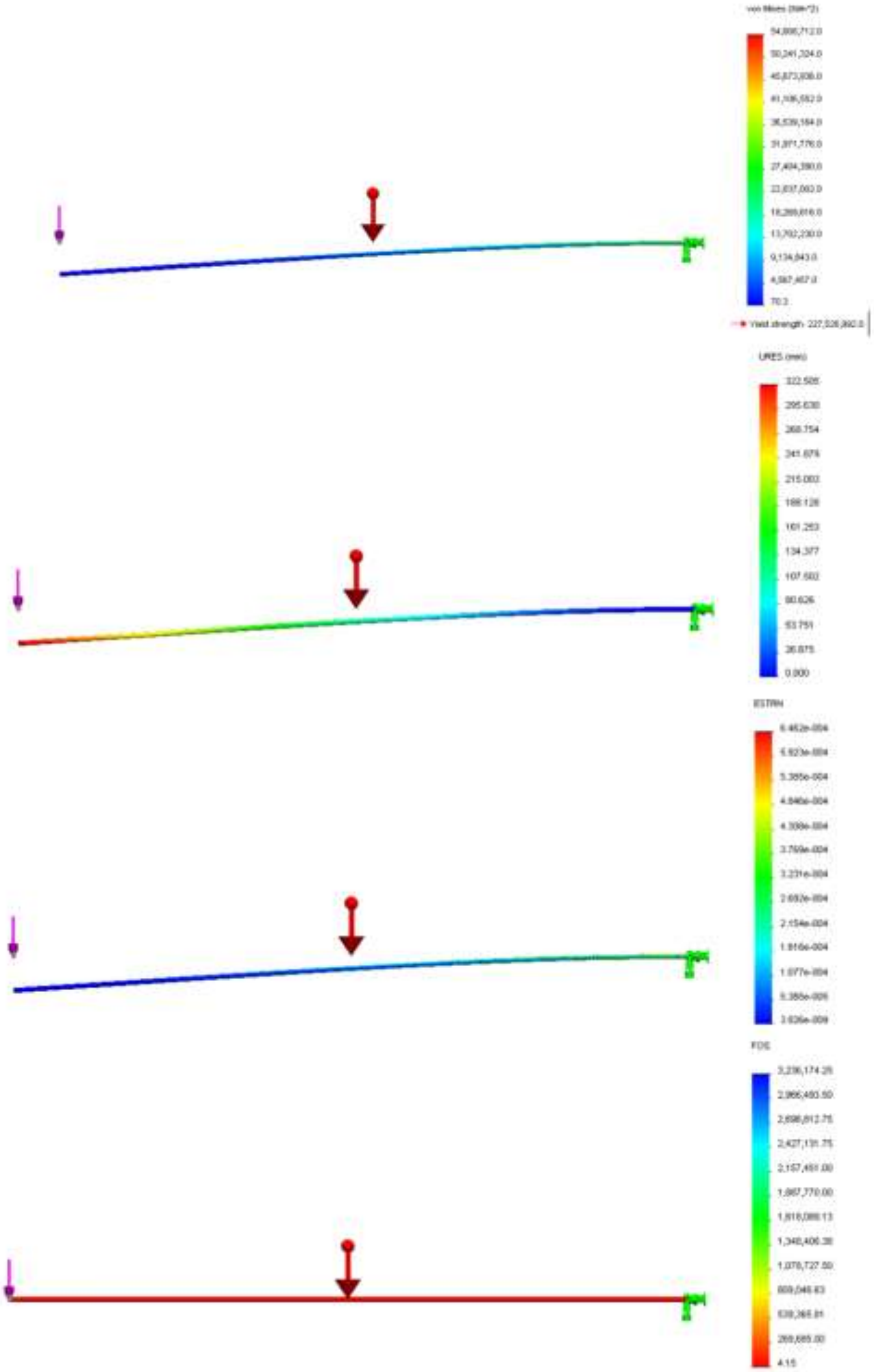

Figure 3-5: Bending Analyses: (From Top to Bottom) Stress, Displacement, Strain, and Factor of Safety

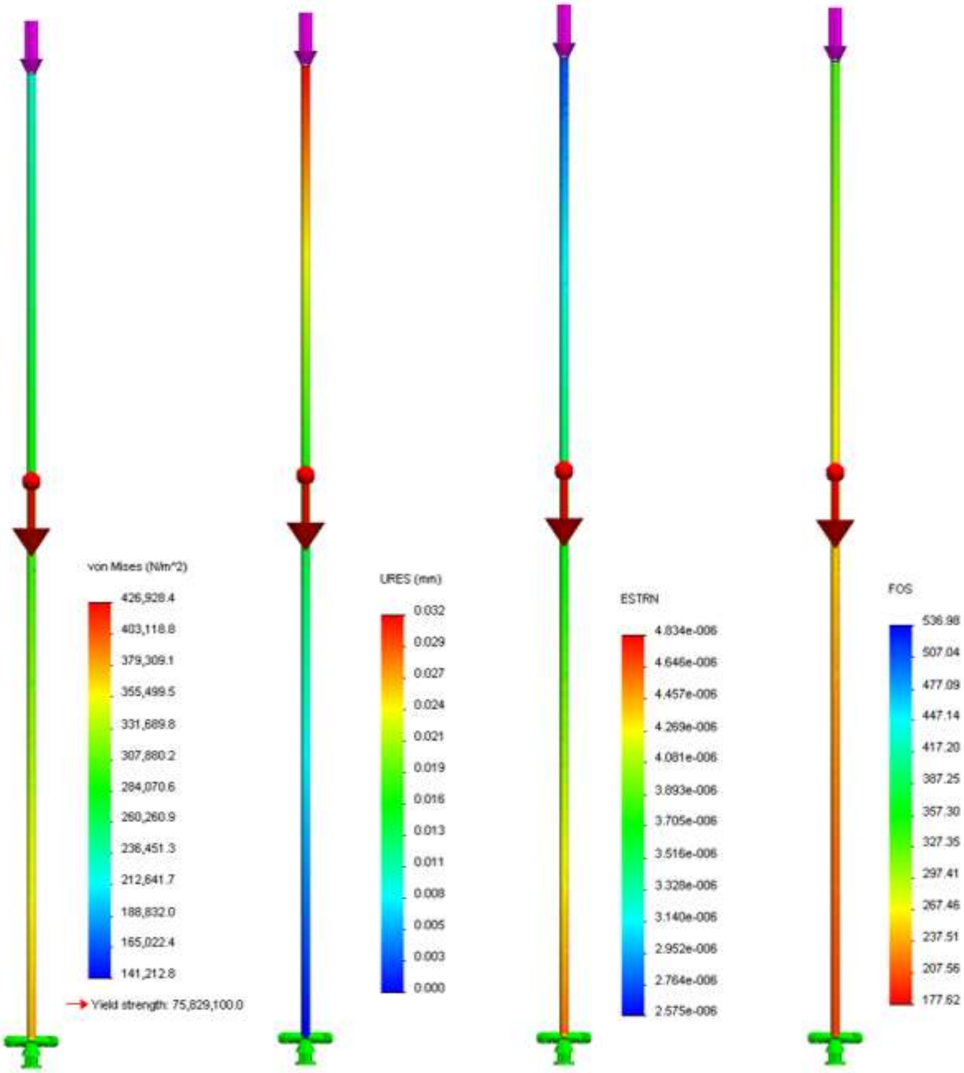

Figure 3-6: Stress, Displacement, Strain, and Factor of Safety (From Left to Right)

Table 3-6 provides a summary of the results obtained from the analyses done. Using the values for maximum stress, obtained using finite element analysis on the tower design with guy wires, the minimum factor of safety was found to be 4.2, occurring while raising the tower.

Table 3-1: Tower Analyses Summary

Analyses With Guy Wire Supports for Max Load	
Top Load from Turbine Weight	60 N
Wind Load	100 N
Tower Height	6 m
Maximum Bending Stress	55 MPa
Bending Factor of Safety	4.2
Maximum Buckling Stress	0.4 MPa
Buckling Factor of Safety	180

3.3 Main frame

The main frame acts as the main supporting structure for the wind turbine by allowing the rotor, hub, gearbox, generator, yawing system, and nacelle to be connected to one structure.

3.3.1 Design


Figure 3-7: Finished mainframe

The mainframe is designed to withstand all loading and act as a completely rigid structure while being small enough to fit behind the shadow of the hub. The mainframe has been constructed from 16 gauge sheet metal and cut to shape using a CNC milling machine. The piece was then bent into shape to provide structural rigidity. This component was then painted with a cold-compound to prevent corrosion. This design makes use of two components to make accessing the generator simple and to allow the mainframe to be used for a direct drive system and a system which utilizes a gearbox. The generator is first mounted onto a bracket which can then be mounted onto to the mainframe. These two components can be seen in **Figure 3-7**. The mainframe supports the provided Great Planes Ammo GPMG 5225 motor, the provided Great Planes GPMG0510 gearbox, a three phase slip ring, the nacelle structure, and provides mounting for the passive yaw system. This system is bolted to the yaw plug located at the top of the yawing system and fastened to the nacelle.

3.3.2 Analysis

Analysis on the mainframe was conducted using Solidworks 2013 structural FEA software. Analysis was ran in order to determine the optimal shape vs. material thickness ratio that would support the structure and act as a completely ridged member. Loading and boundary conditions were applied to the main frame during the analysis with values of the loads shown in **Table 3-2** and their specific loading locations shown in **Figure 3-8**. Given the loading conditions analysis solving for the maximum displacement and maximum stresses within the structure were calculated.

Table 3-2: Static Structural Loading Conditions

Static Structural Loading Conditions	
Boundary Conditions (1)	Fixed
Thrust Load (2)	30 N
Nacelle Weight (3)	20 N
Electronics Weight (4)	30 N
Gravitational Effect (5)	9.81 m/s2

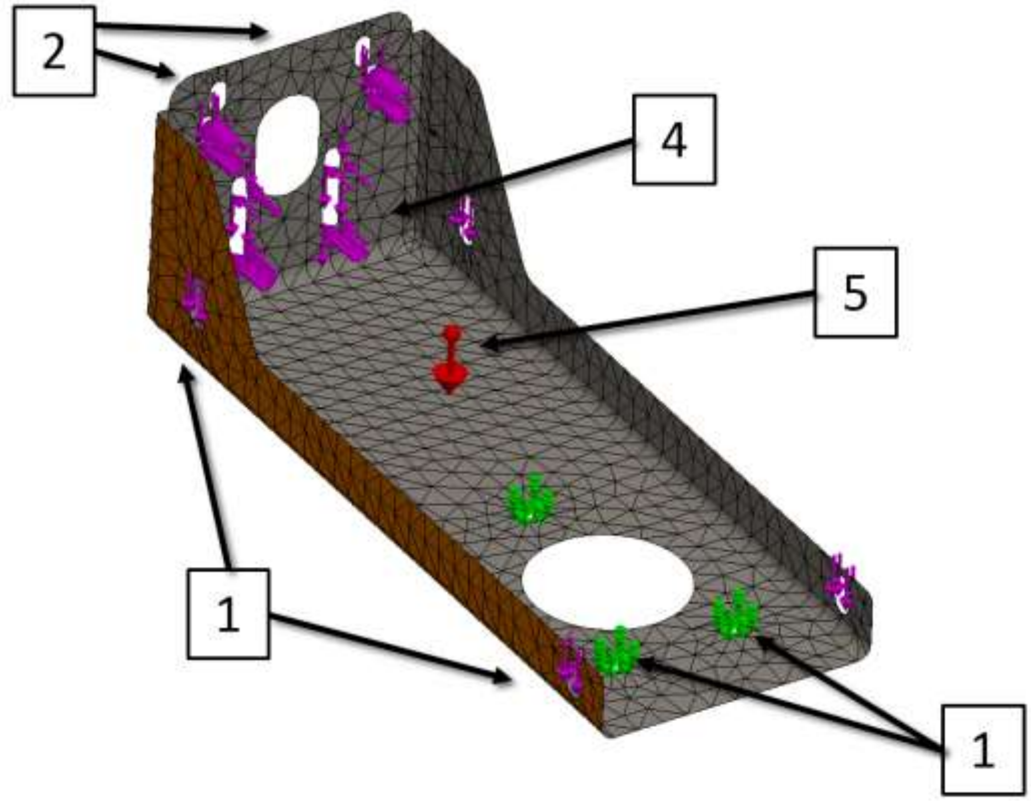

Figure 3-8: Structural loading conditions for mainframe

Calculation of critical stresses within the structure and their locations was conducted through the use of FEA. Using the loading conditions as previously mentioned in **Table 3-2** with an equal length triangular element mesh applied to the structure, locations of critical stresses were calculated (**Figure 3-9**).

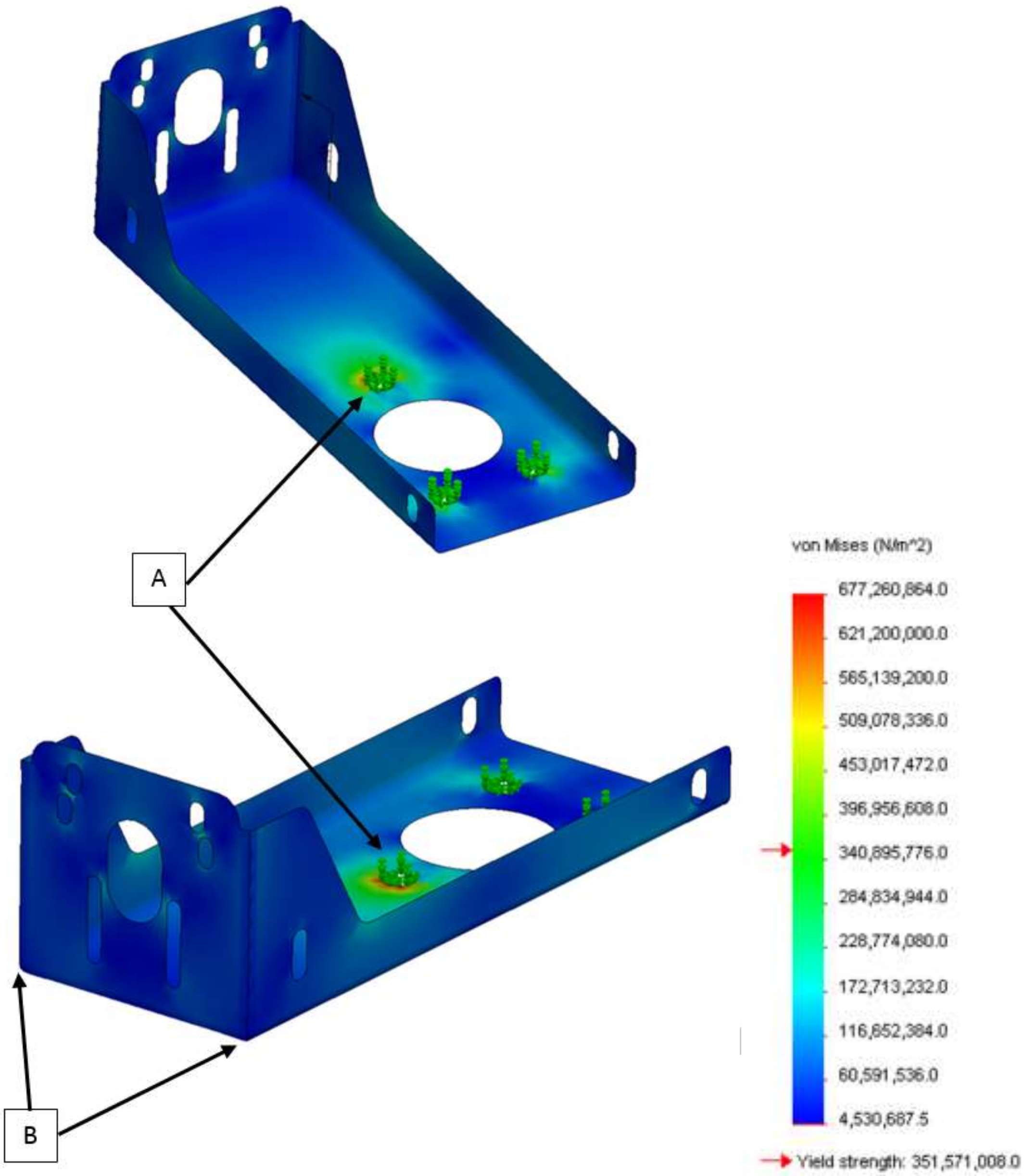

Figure 3-9: Main frame von-Mises stress calculation

Maximum stress was calculated occur at the bolt whole locations [A] where the main frame will be bolted and have a von-Mises stress of 677MPa. However, the analysis was assuming that the members were only fixed at those bolt-hole location with not supporting structure underneath them, thus making the von-Mises stress at location [A] inaccurate. The members of interest within the structure are actually along the weld points [B]. Location [B] is considered the section of interest because it is where the largest force and moment will be applied in the system. At these points of interest the maximum von-Mises stress in the system is calculated to be 172 MPa with a minimum factor of safety of 2.03. A summary of these results for the von-Mises stresses in the main frame are shown in **Table 3-3**.

Table 3-3: Maximum von-Mises Stress for main frame

Maximum von-Mises Stress	
Critical Stress (A)	677 MPa
Stress at Location of Interest (B)	172 MPa
Factor of Safety at (B)	2.03

In addition to calculation of the von-Mises stress within the system, maximum deflection of the loaded main frame was calculated. **Figure 3-10** shows the maximum deflection of the main frame when the loading conditions mentioned in **Table 3-2**. In order for the main frame to be considered as a ridged member, the maximum allowed deflection within the structure was assumed to be 2 mm or less. Calculations from the FEA solution calculated the maximum displacement in the horizontal direction was calculated to be 1.63mm with deflection in the vertical axis of 0.95mm (**Table 3-4**), thus all requirements for a ridged structural member were met.

Table3-4: Deflection of Main Frame when Loaded

Deflection of Main Frame when Loaded	
Maximum Horizontal Deflection	1.63 mm
Maximum Vertical Deflection	0.95 mm

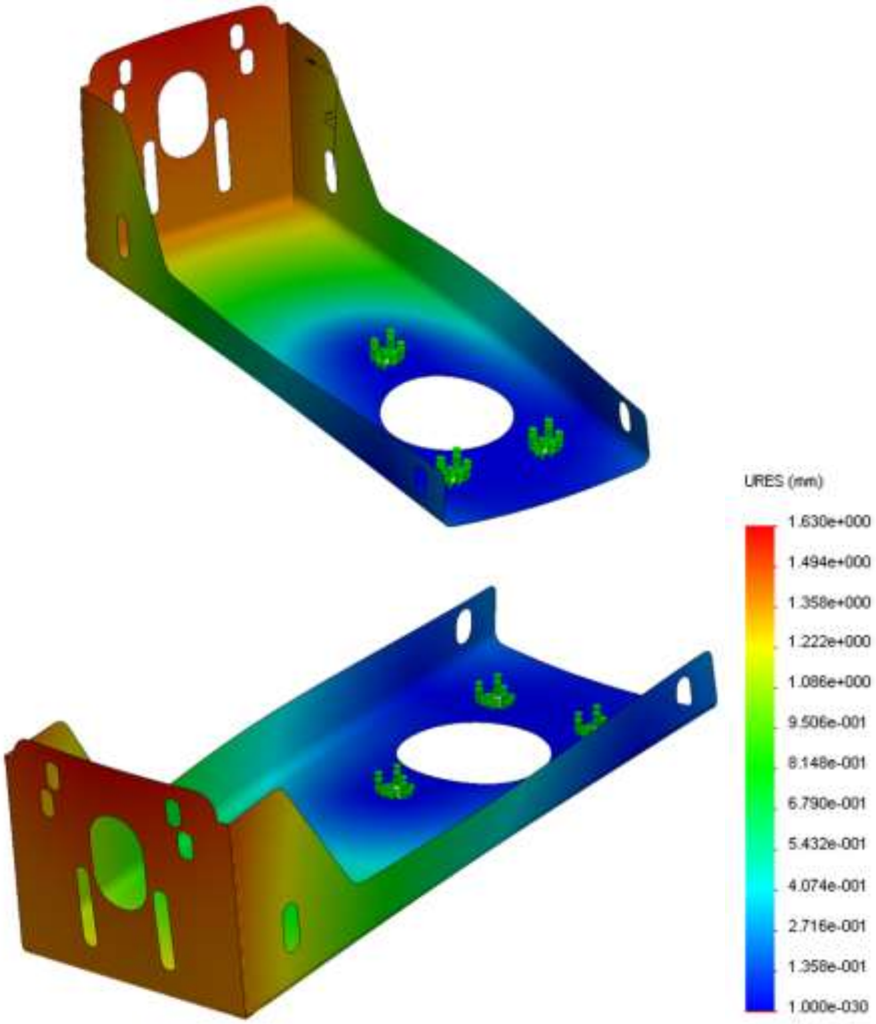

Figure 3-10: Main frame displacement calculation

3.4 Yawing system

The yawing system allows the turbine to freely rotate 360° to better direct the blades into the wind for better power production.

3.4.1 Design

Figure 3-12: Section View of Yawing system

The turbine utilizes a passive yawing system which allows the blades to be directed into the wind. The yawing system design consists of two single row, deep groove ball bearings, a three phase slip ring, a threaded base plug, a yaw sleeve, an upper yaw plug, and a yaw shaft. A sectional view of the yawing system can be seen in **Figure 3-11**. The yaw shaft is threaded into a plug at the base of the system. The two bearings and plastic bearing spacers sit on the shaft and an aluminum sleeve fits over the top with a plug press fit into the top. **Figure** 3-11**3-12** shows the yawing system with the mainframe, slip ring, and generator attached.

Figure 3-11: Final Yawing System

3.4.2 Analysis

The bearing analysis completed for the yawing system was used to select bearings that would work for the turbine design. This analysis was done assuming a maximum load of 490N which would occur when while the tower was being hoisted. **Figure 3-13** shows the diagram that was used to find bearing loads. The maximum resultant load occurs on bearing A and was found to be 646N. This value was used to solve for the dynamic load (C10 value) on the bearings of 12kN. With this analysis two SKF 6006-Z single row, deep groove ball bearings were selected for the design.

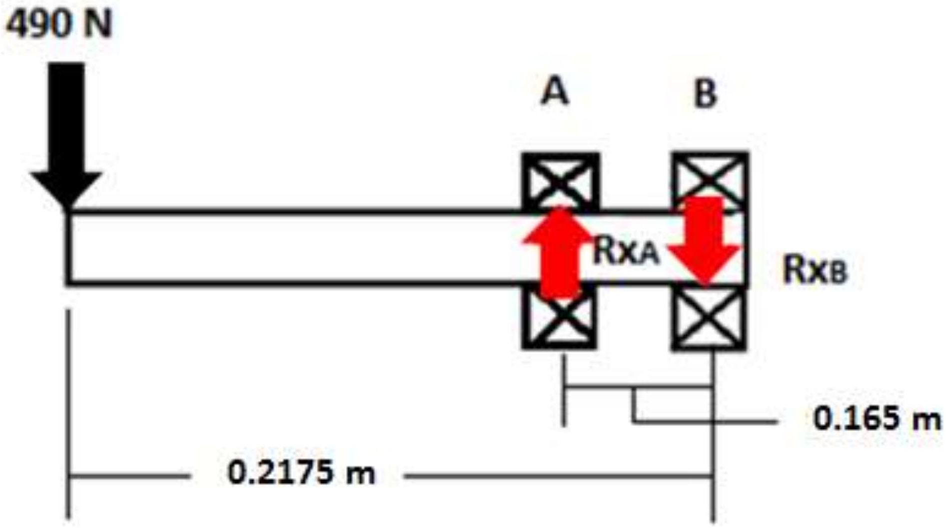

Figure 3-13: Yaw shaft bearing analysis

3.5 Nacelle

The nacelle acts as a cover for the generator, main frame, and slip-ring to protect critical components from the environment. In addition the nacelle constructed with a faired section that covers the yawing system to reduce turbulent affects from the wind into the blades.

3.5.1 Design

The nacelle was designed around the dimensions of the mainframe and the hub. The nacelle is only slightly larger than the hub to lessen inefficiencies as air flows over the nacelle and to the blades. A removable door has been built into the top half of the nacelle to ensure that components can be properly placed and to allow components to be fully inspectable, this can be seen in **Figure 3-14**. The top portion of the nacelle is attachable by screws and a small tab built into the top portion of the nacelle. The bottom portion has holes drilled into it, which will attach it to the mainframe.


Figure 3-14: Nacelle


Figure 3-15: faired tower section

A nacelle is also integrated with a faired tower section seen in **Figure 3-15** that encases the yawing system and allows for less turbulent wind flow across the turbine tower. This minimizes vortex shedding due to the wind flowing over the trailing edge of the tower, reducing inefficiencies as the turbine blades pass behind the tower. This aerodynamic casing was been integrated into the nacelle design to create a sleek and aesthetically appealing design.

3.5.2 Analysis

For the nacelle analyses was done using Solidworks Fluid Flow Simulation. Air was placed around the nacelle and faired tower section and was set to a velocity of 14 m/s. **Figure 16** shows that at a velocity of 14 m/s the nacelle will reduce the velocity at the blades to around 10 m/s. This is a large decrease, but as the nacelle is already as close to the main frame as possible is ideal as it can get.

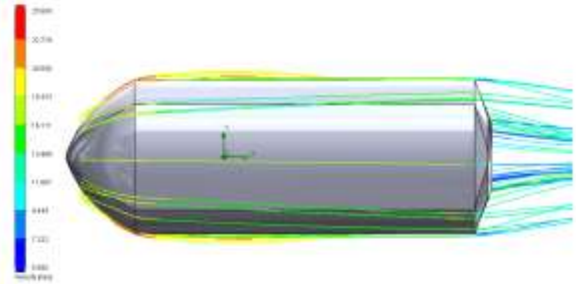
Figure 3-16: Top view of Nacelle with a wind speed of 14 m/s

Likewise to the nacelle, analysis was also done on the faired tower section to compute the ideal taper angle. Several iterations of this analysis was completed with differing taper angles to determine which angle would work best at the rated wind speed (12 m/s). Based on results of the velocity flow profile and flow trajectory plots analyzed in **Figure 17&18**, a 12 degree taper angle was found to be the best for angle for this application. Flow simulations were also done at the cut in and cut out wind speeds of 4 m/s and 17 m/s for the chosen taper angle in order to verify results.

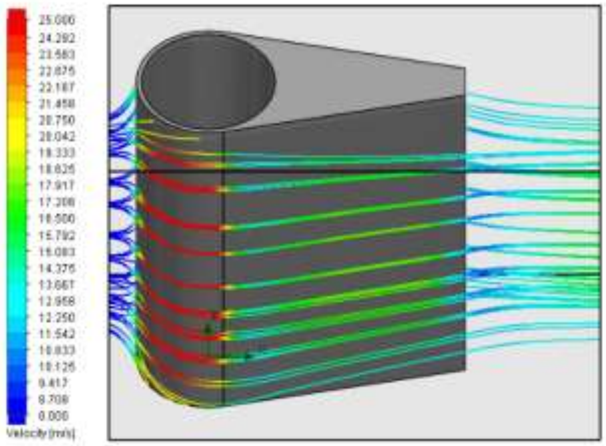

Figure 3-17: Flow Trajectories/Velocity Profiles for 12m/s

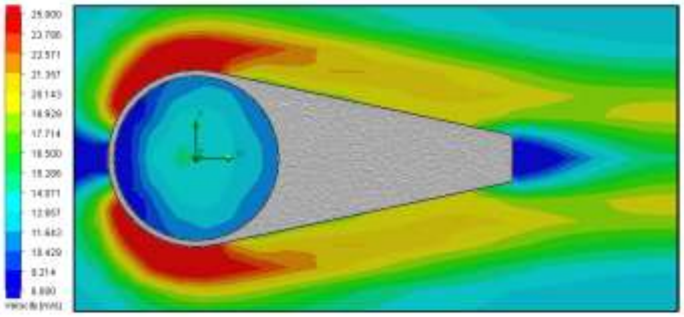

Figure 3-18: Velocity Contour Play at 12m/s

Chapter 4. Prototype Fabrication

4.1 Base

For the base the layout was done on the pieces to indicate where the cuts and bends needed to be done. The individual pieces were cut to size using a floor shear and an angle shear. The sides that were needed were bent using the bending machine. Once all of the pieces bent to their desired specifications, the holes for the stakes and wiring were punched through the base. Furthermore, the individual pieces were welded together. First, the two bottom plates of the base were welded together. Once that was done, the proper placement of the vertical pieces were laid out and the vertical pieces were tack welded to the two bottom plates of the base. With that done, the shelf supports and shelf were welded onto the base last. **Figure 4-1** shows the base with the bottom two plates and vertical sections welded together.

Figure 4-1: Base welding

4.2 Tower

The tower included one part that needed to be made, and was manufactured using the CNC machine and then bent on the sides and one alteration to the tower itself. The guy wires were clipped down to the thimble to attach them to the guy wire attachment. The rest of the tower was assembled by screwing parts together. The alteration to the tower included drilling of a hole at the base of the tower to allow a bolt to be slipped through for mounting purposes.

4.3 Main frame

Manufacturing of the main frame structure required the use of CNC machining in order to obtain the accuracy and desired shape. Since CNC work was required for this plate the use of CATIA V5 CAD software suite was used to design and write NC-code, which in turn was used for CNC milling. The material stock that was used for the first prototype was 16 gage inch thick steel sheet metal. The milling operations utilized a 1/8” high speed steel end mill and the Tormach CNC milling machines to mill out the slots, holes and profiles of the main frame (**Figure** 4-2**4-2**).

Figure 4-2: Manufacturing of the main frame using the Tormach CNC mill

The resulting milling process produced the desired main frame profile cutout as shown in **Figure 4.3**. Bending of the side supports of the main frame was conducted with the help of a mechanical bender.

Figure 4-3: Profile cutout for the main frame

4.4 Yawing system

For the yawing system two plugs were created that are used to attach the yawing system to the main frame and the tower (**Figure 4-4**). Both of these parts were made using aluminum rod, that was shaved down on the lathe and then a tap was made from a manual tap. The shaft for the yawing system was also shaved down on the lathe and then tabbed the outside of the shaft manually.

Figure 4-4: Yaw plugs

For assembling the yawing system the sleeves and spacers were cut on the band saw then sanded down to the exact size wanted. Once all pieces were completely the plugs were press fitted into the tower and sleeve using a hydraulic press. The other parts were assembled along the shaft to complete the yawing system.

4.5 Nacelle

To manufacture the nacelle it was designed using solidworks, and then rapid prototyped using ABS and ultem plastic. Two different materials were used due to malfunctions with one of the larger RP machines (**Figure 4-5**). Additionally, the top half of the nacelle was printed into separate sections with the ability to remove top section for necessary repairs (**Figure 4-5**).

Figure 4-5: Prototyped nacelle (Left); Finished and painted nacelle (Right)

After the nacelle was printed, it was painted with galvanizing spray and a dark blue paint. This was don’t to smoothen out the surface and add aesthetic appeal to the turbine assembly.

Chapter 5. Testing and Results

5.0 Introduction to Testing

Testing was conducted using a wind tunnel to determine that overall effectiveness of the wind turbine as a complete system. Testing results included analyzing the effectiveness of varying designs and component combinations. Tests that were conducted with within the wind tunnel (**Figure 5-1**) included cut-in wind speed, rated RPM, and cut-out wind speed.

Figure 5-1: Wind tunnel used for wind turbine testing

These tests were performed with regards to three different scenarios:

- Using the completion supplied generator (**Figure 5-2**) with the nacelle attached
    - Generator has high cogging torque and poor power production characteristics
- Using the completion supplied generator without the nacelle attached
- Using the business plan specified generator (**Figure 5-2**) with the nacelle attached
    - Generator has lower cogging torque and better power production characteristics

Figure 5-2: Completion specified generator (Left); Business plan specified generator (Right)

5.1 Cut-In Wind Speed

Testing regarding cut-in wind speed was determined by mounting the completed turbine assembly within a wind tunnel and documenting at which wind speeds the rotor of the wind turbine would start spinning at. In order to achieve cut-in the turbine must overcome the cogging torque within the generator, which typically requires relatively high wind speeds. This test compared two different design options which consisted of the turbine assembly with and without a nacelle. Multiple test runs were ran with the data averaged over multiple tests for the most accurate data as possible.

5.1.1 Results

Cut-in wind speed for the completed turbine assembly with and without the nacelle attached resulted in mixed results. **Figure 5-3** shows at what wind speed the blades were able to overcome the cogging torque of the generator.

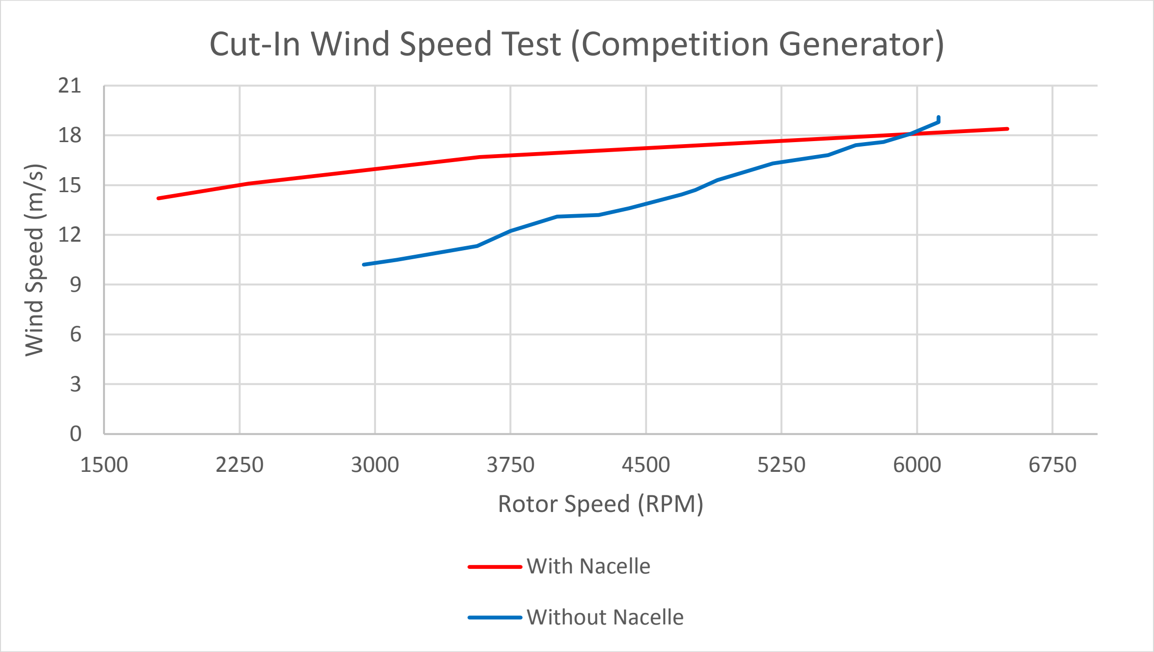

Figure 5-3: Cut-in wind speed data

As expected with the flow analysis of the nacelle, the turbine required a 29% increase in wind speed in order to overcome the cogging torque of the generator and achieved cut-in at 14.2 m/s. With the nacelle removed, cut-in was achieved at a wind speed of 10.2 m/s (**Table 5-1**).

Table 5-1: Cut-in wind speed and rated rotor speed summary

Test	With Nacelle	Without Nacelle
Cut-In Wind Speed	14.2 m/s	10.2 m/s
Maximum Rotor Speed (18 m/s)	4000 RPM	5661 RPM

Even though cut-in was reduced due to the boundary layer effects of the nacelle, performance at higher wind speeds was greatly increased with the blades achieving hysteresis of 6000 RPM's at a lower wind speed than without the nacelle.

5.3 Rated RPM

Rated RPM is important for the reasoning of determining at what wind speed the rotor and system will reach a maximum speed. Determination of the maximum speed of the rotor is required to develop a power curve and asses the efficiency of the system.

5.3.1 Results

Rated RPM was determined to be achieved with a wind speed of 17 m/s, which is the fastest wind speed the system will experience during testing at competition. At a wind speed of 17 m/s the blades achieved a maximum RPM of 4000 with the nacelle attached and 5661 without the nacelle (**Table 5-1**).

5.4 Cut-Out Wind Speed/Ability to Yaw

Cut-out wind speed is important in order to determine the characteristics of the system when spinning and producing power. Cut-out determines at what wind speed the rotor and system stops to function once the blades are rotating. As conducted with cut-in wind speed, multiple test runs were conducted with the averages of all runs calculated for best results.

In addition to performing cut-out wind speed tests, the turbine assembly was positioned at angles varying between 0-90° to test the system's ability to yaw. Numerical results were not obtained as for this was a pass/fail type test. Results for the ability to yaw tests are presented in **Table 5-2**.

5.4.1 Results

Cut-out wind speeds were tested using three different scenarios. The first scenario used the completion specified generator (**Figure 5-2**) with the nacelle attached. The second scenario used the completion specified generator without the nacelle. The final scenario used the generator specified by the business plan (**Figure 5-2**) with the nacelle attached. Data was obtained for each scenario and compared using **Figure 5-4**.

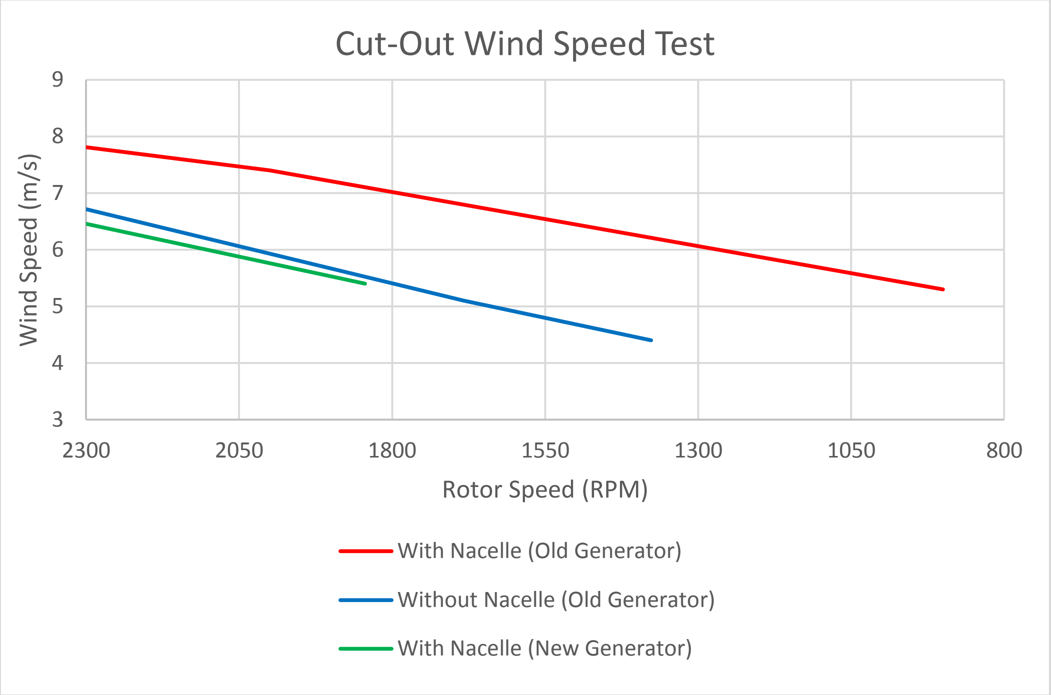

Figure 5-4: Cut-out wind speed data

As seen from **Figure 5-4**, the scenario that lasted the longest without cutting out was the system that did not have the nacelle. Comparison between the scenarios with and without the nacelle show that even the effect the nacelle has on the blades at low wind speeds affects is obvious regardless of the generator used. Results of these three scenarios for determination of cut-out wind speeds are presented in **Table 5-2**.

Table 5-2: Cut-out wind speeds and ability to yaw testing summary

	Cut-Out Wind Speed (m/s)	Ability to Yaw
With Nacelle (Old Generator)	5.2	Yes
Without Nacelle (Old Generator)	4.4	Yes
With Nacelle (New Generator)	4.8	Yes

Chapter 6. Cost Analysis

6.0 Introduction to Cost Analysis

The cost of the turbine for team 20's components includes all the material costs and the manufacturing cost assuming the worker gets $15 an hour. The total cost for the just the turbine, the turbine with the tower and base, and the amount team 20 spent is computed.

The total cost for the full turbine, including blades and electrical components is also included.

6.1 Cost of the Base

6.1.1 Materials

For the base, the structural material chosen is 16 gauge. The material was chosen to be steel to limit weight while being structurally sound. Grade 8 locknuts and hex head cap screws were used to secure the tower to the base because they were found to have suitable properties to resist shear. The base was painted with galvanizing and zinc spray to prevent. The base will cost around $38.00for the prototype and then become slightly cheaper as more unites are produced at once. The total cost can be seen below in **Table 6-1**.

Table 6-1: Summary of Base Material Cost

Base Material Cost								
Material	Size	Quantity	Cost per unit($)	Prototype cost ($)	1 ($)	5 ($)	25 ($)	50 ($)
16 Gauge Steel	2' by 2 '	4	5.32	21.28	21.28	101.08	478.80	861.84
Bult	3/4 inch	1	5	5.00	5.00	23.75	112.50	202.50
High-Strength Steel Cap Screw - Grade 8,	3/4"-16 Thread, 6" Long	1	6.29	6.29	6.29	28.31	125.80	226.44
cold-galvanizing and zinc spray	One can	2	5.00	10.00	10.00	10.00	40.00	80.00
10 Grade 8 Steel Nylon-Insert Hex Locknut	3/4"	1	5.82	5.82	5.82	26.19	116.40	209.52
total cost per unit				**38.39**	**38.39**	**37.87**	**34.94**	**31.61**

6.1.2 Manufacturing

To construct the base it will be essential to manipulate all of 16 gauge steel into the required shapes for the design. The parts that will be manipulated from steel sheets are the base plate, shelf supports, tower mounting plates, battery shelf, and vertical supports. The estimated manufacturing time on all of the steel components was estimated to be 20 hours. The welding of the base is expected to take about 3 hours to complete (**Table 6-2**).

Table 6-2: Summary of Manufacturing Costs

Base Manufacturing							
Component	hours	Hour rating ($/hour)	Prototype Cost ($)	1 (hours)	5 (hours)	25 (hours)	50 (hours)
Bending and cutting	9	15	135.00	8	8	7	6.5
Welding	3	15	45.00	2.5	2.5	2.5	2.5
Total cost per unit			**180.00**	**157.5**	**157.5**	**142.5**	**135**

6.2 Cost of the Tower

6.2.1 Materials

The cost of the tower materials includes 3 sections of 6 foot piping and 3 threating pipe fittings to connect them. Three eye nuts will be used on the tower to connect the guy wires to the tower, and 100 feet of cable for the guy wires. Overall the tower will be the major cost for the project (**Table 6-3**).

Table 6-3: Summary of Tower Material Cost

Tower Material							
Parts	cost per unit	quantity	prototype	1 ($)	5 ($)	25 ($)	50 ($)
Standard aluminum pipe OD 1.5 l = 6	$102.40	3	307.20	307.20	$1,459.20	6,912.00	6,566.40
Standard aluminum pipe OD 1.5 L = 3	$51.05	1	51.05	51.05	$242.49	1,148.63	2,067.53
Pipe couplers	$5.68	3	17.04	17.04	$80.94	383.40	690.12
wire rope clips	$0.99	4	3.96	3.96	$18.81	89.10	160.38
thimble	$0.95	8	7.60	7.60	$36.10	171.00	307.80
Primer	$5.27	1	5.27	5.27	5.27	26.35	47.43
Sleeves	$0.25	4	1.00	1.00	$4.75	22.50	40.50
1/16" guy wire (130ft)	$0.11/ft	130 ft	14.30	14.30	$67.93	321.75	579.15
Total Cost per unit			**407.42**	**407.42**	**383.10**	**362.99**	**209.19**

6.2.2 Manufacturing

Minimal manufacturing will need to go into building the tower. The major manufacturing component of the tower will be creating the guy wire attachment plate that is expected to take 2 hours to build the first time, then as the manufacture gets quicker at creating it the time allotted for it will go down (**Table 6-4)**.

Table 6-4: Summary of Tower Manufacturing Cost

Tower Manufacturing							
				1	5	25	50
Component	hours	Hour rating ($/hour)	Prototype Cost ($)	1 (hours)	5 (hours)	25 (hours)	50 (hours)
tower prep	2	15	$ 30.00	2	1.5	1	1
Guy Wire attachment plate	1	15	$ 15.00	1	1	0.75	0.5
Total			**$ 45.00**	**45**	**37.5**	**26.25**	**22.5**

6.3 Cost of the Main frame

6.3.1 Materials

The main frame has been greatly reduced in size and material then previous designs. It is now made from 16 gauge steel and will only cost around $1.50 for the total parts (**Table 6-5)**.

Table 6-5: Summary of Main Frame Material Cost

Mainframe Material							
Material	Size	Quantity	Prototype ($)	1 ($)	5 ($)	25 ($)	50 ($)
16 gauge 0 Steel Sheet	12"*12"*.125	1	1.5	1.5	6.75	30	50
total cost per unit			1.5	1.5	1.35	1.2	1

6.3.2 Manufacturing

The manufacturing of the mainframe includes the computer numerical controlled cutting of the shape, bending and welding of the part. The prototype took an hour and a half to create, and the cost is expected to decrease over time (**Table 6-6)**.

Table 6-6: Summary of Main Frame Manufacturing Cost

Mainframe Manufacturing							
Component	hours	Hour rating ($/hour)	Prototype Cost ($)	1 (hours)	5 (hours)	25 (hours)	50 (hours)
mainframe	1.5	15	22.5	1.5	1.5	1	0.75
total price per unit			22.5	22.5	22.5	15	11.25

6.4 Cost of the Yawing System

6.4.1 Materials

The yawing system contains four major parts, the bearing, the slip ring the shaft and the two plugs. All of these can be found relatively cheap; however the price added together was $133.00, and will decrease as parts are bought in bulk (**Table 6-7)**.

Table 6-7: Summary of Yawing System Material Costs

Yaw System Material							
Parts	cost per unit	quantity	total	1 ($)	5 ($)	25 ($)	50 ($)
Bearings	$12.95	2	25.90	25.90	$123.03	582.75	1,048.95
slip ring	$39.99	1	39.99	39.99	$189.95	899.78	1,619.60
sleeve	$36.64	1	36.64	36.64	$174.04	824.40	1,483.92
Large spacer	$8.25	1	8.25	8.25	$37.13	165.00	297.00
aluminum for plugs	$7.00	1	7.00	7.00	$25.00	125.00	225.00
Shaft	$15.00	1	15.00	15.00	$71.25	337.50	607.50
Total yawing system			132.78	132.78	124.08	117.38	105.64

6.4.2 Manufacturing

The shaft and the plugs take the majority of the time to manufacture, taking 3.5 hours each. Another half an hour was added for cutting the spacers and assembling all the parts (**Table 6-8**).

Table 6-8: Summary of Yawing System Manufacturing Costs

Yawing System Manufacturing							
Component	hours	Hour rating ($/hour)	Prototype Cost ($)	1 (hours)	5 (hours)	25 (hours)	50 (hours)
shaft	3.5	15	$ 52.50	3	2.5	2	2
Plugs	3.5	15	$ 52.50	3.5	3.5	3	2.5
other	0.5	15	$ 7.50	0.5	0.25	0.25	0.25
total			$ 112.50	105	93.75	78.75	71.25

6.5 Cost of the Nacelle

The Nacelle is a complex design that will be produced differently depending on the amount of turbines being made at one time. For the prototype the nacelle is made out of rapid prototype using donated material and equipment, but if it were to be produced on a large scale it will be made from mold injection and will be outsourced to another company for simplicity and cost (**Table 6-9)**.

Table 6-9: Summary of Nacelle Material Costs

Nacelle					
Material	Cost ($)	1 ($)	5 ($)	25 ($)	50 ($)
Mold	20	20	90	375	600
injection	80	80	400	1875	3250
total cost per unit		100	98	90	77

6.6 Total Cost

The total production of one prototype unit is ended up being $1067 for material. The price was also found of just the main frame assembly, which includes everything but the tower and base. This is so costumers will have the option to mount their turbine on their own roof or tower and reduce their cost greatly. The total cost for the mainframe assembly is $369 for the prototype. As more unites are made the price starts to decrease. The percent difference can be seen in **Table 6-10**.

Table 6-10: Total Cost of Turbine

Total Cost					
	Prototype	1 ($)	5 ($)	25 ($)	50 ($)
Main frame asm	234	234	1037	5018	9082
main frame asm labor	135	128	656	2906	5438
total	369	362	1694	7924	14519
total per unit	**369**	**362**	**339**	**317**	**290**
Overall Total	1067	1037	979	904	826
Percent different		3%	9%	18%	29%

The total expected cost for the full turbine including all components such as the blades and electrical components is shown in **Table 6-11**. The numbers were found assuming multiple products were being made with around 100 turbines, and 25 turbine and towers being sold.

Table 6-11: Full Assembled cost

Full assembly cost		
	Total cost	Marketed price
Turbine	$903.00	1500.00
Turbine and tower	$1421.00	2400.00

A lot of the materials were donated to team 20, and therefor were not included in the price the prototype for the team cost. The team decided that because the turbine will only be on display with the tower, it was decided to be a scaled down version by 1/3. The material purchased can be seen in **Table 6-12**.

Table 6-12: Team 20's cost

Material	cost ($)
full yawing system	125
Tower parts	155
Base and mainframe material and equipment	50
Paint	15
Other (nuts, bolts etc.)	20
Total	$365

Chapter 7. Conclusion

The Balance of System and Testing Team was tasked with designing a micro wind turbine for the United States Department of Energy inaugural Collegiate Wind Competition. The main liaisons for the team are Karin Wadsack (Lead Professional Investigator) and David Willy (Faculty Advisor). The purpose of the wind turbine is to charge small electronics in post disaster scenarios where it is not economically viable to continually transport fuel to run generators.

For each of the parts the proposed design was described detailing each part. The base is a portable box that allows for the tower to be easily raised. It has four holes in it that can be used to mount the base to the ground using anchors. For the tower, a monopole design with guy wires is used. The tower consists of 4 different sections where the bottom three are 6 feet long and the top section is 3 ft long. They will each be attached to each other using threaded couplers. Guy wires will be attached using a plate placed at 18 feet up the tower (oh the third 6 foot section), and will be used to raise, lower and stabilize the tower. The yawing system is passive yaw with two ball bearings, a three electrical lead slip ring, and two plugs that will be press fitted to attach the yawing system to the main frame and the tower. The main frame will be made out of 16 gauge steel and be a bedplate design that is just large enough to fit the generator and attach easily to the hub. Finally the nacelle was designed to have be as closely fit as possible to the main frame and will incorporate a faired tower section that will help direct the airflow around the tower section to the blades.

Analysis was done on all major components. The analysis done on the base was the shear on the bolt holding the tower upright and on the factor of safety to make sure the material will be strong enough. For the tower the analysis was done with the guy wires set up to assist the tower in remaining upright, and was done for a monopole design to decide if aluminum will be strong enough. On the yawing system, bearing analysis was done to find the number of bearings to use and the type of bearing needed. After the analysis was run, it was decided to use a two bearing system with a three phase slip ring. Analysis was performed on the nacelle and faired tower section to ensure that the wind flow trajectories would allow for adequate flow velocity into the blades. Lastly, analysis was done on the main frame using Solidworks FEA because of the complexity of the geometry. The analysis was done to find the maximum deflection, find the value and location of critical stress, and the minimum factor of safety on the main frame.

With the components selected and finalized, a cost estimation was formulated. The material cost of the base was $48.00 and estimated manufacturing cost was $180. The tower components were found to be $407.50 in material cost and $45.00 to manufacture. To construct the mainframe, roughly $5.00 worth of material is needed with an additional $22.50 needed for manufacturing cost. For the yawing system, $133.00 will be needed in material cost and will require $112.50 to manufacture. Lastly, the nacelle will cost $100 when outsourced to another company to manufacture. In total, the production cost of the turbine alone is $369.00 for the prototype and $1067.00 including the base and tower. When manufactured in bulk the pricing of the turbine decreases by up to 29 percent when 50 units are made. In the end team 20 had most of the parts donated and only ended up spending a total of $365.00

Acknowledgments

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- The Department of Energy for hosting this competition

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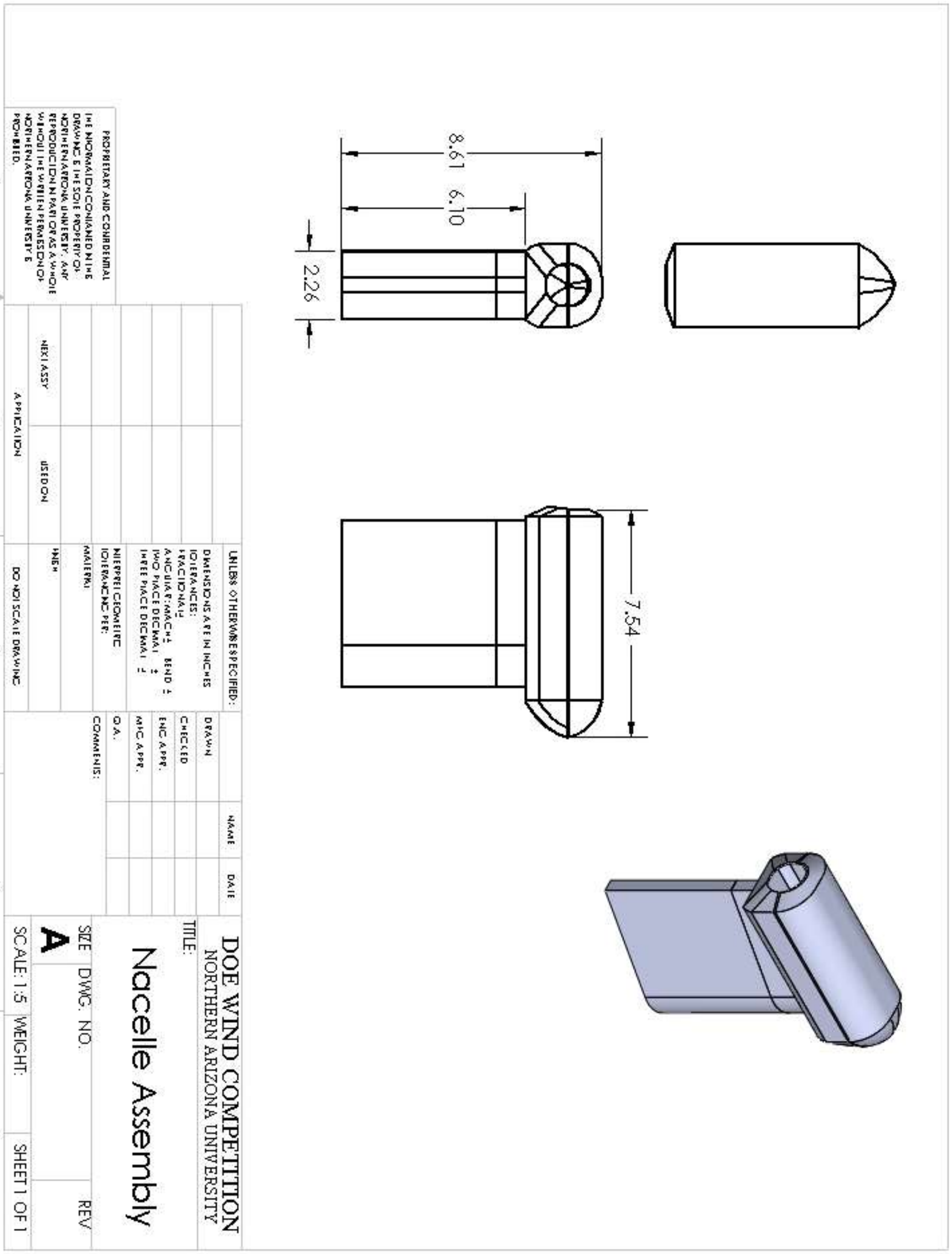
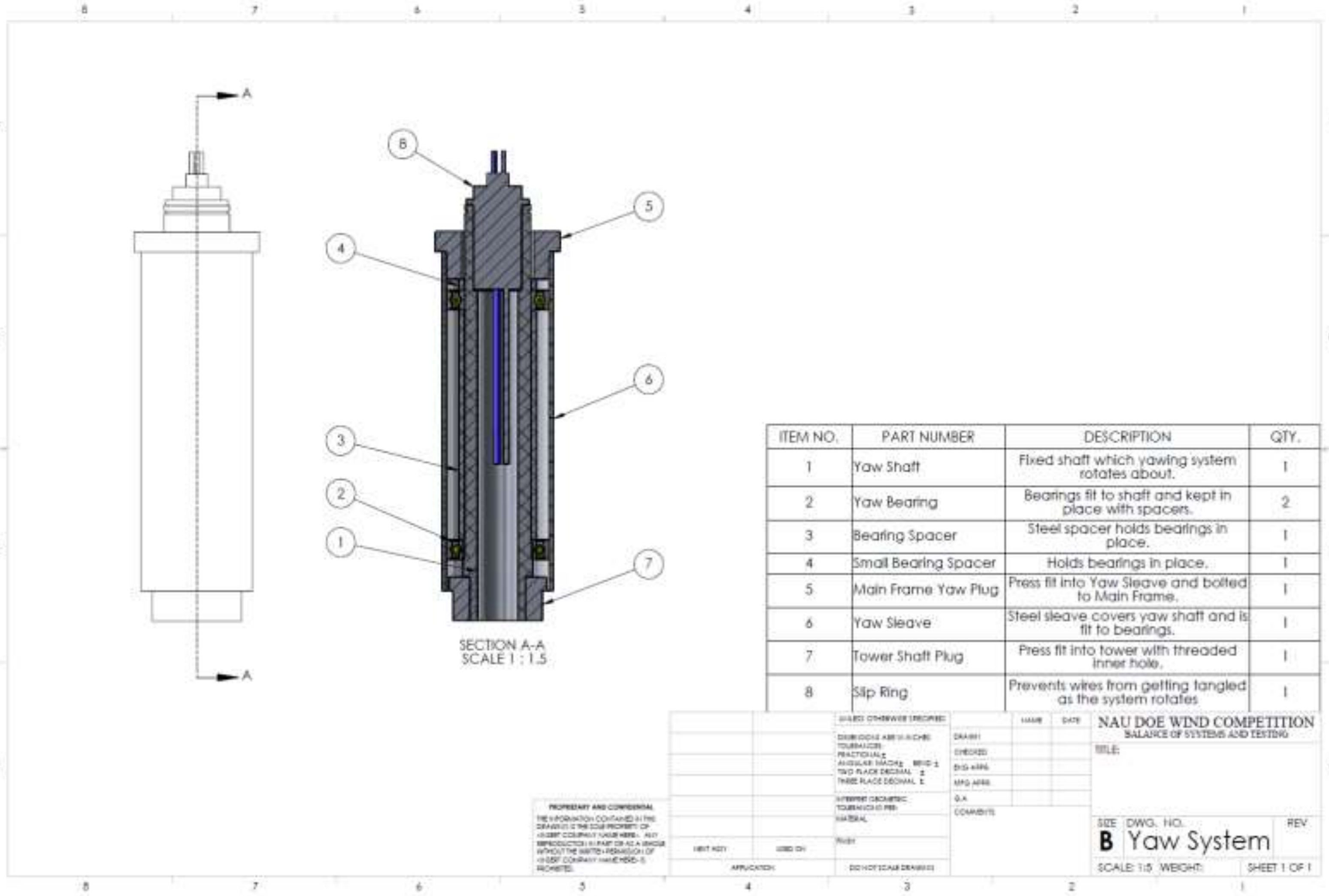
Appendix A: Engineering Drawings

Nacelle Assembly Drawing

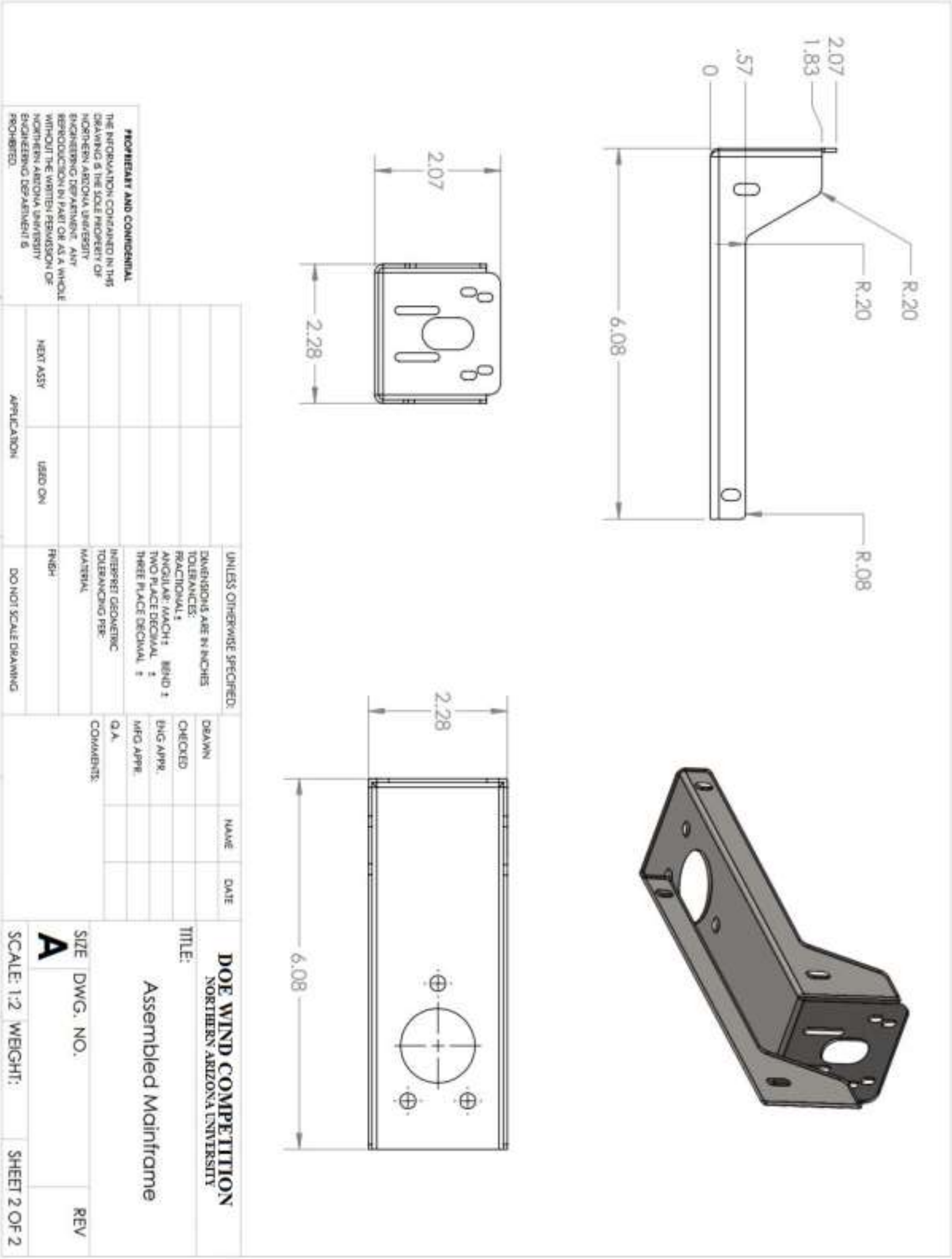


Yawing System Sectional View Drawing

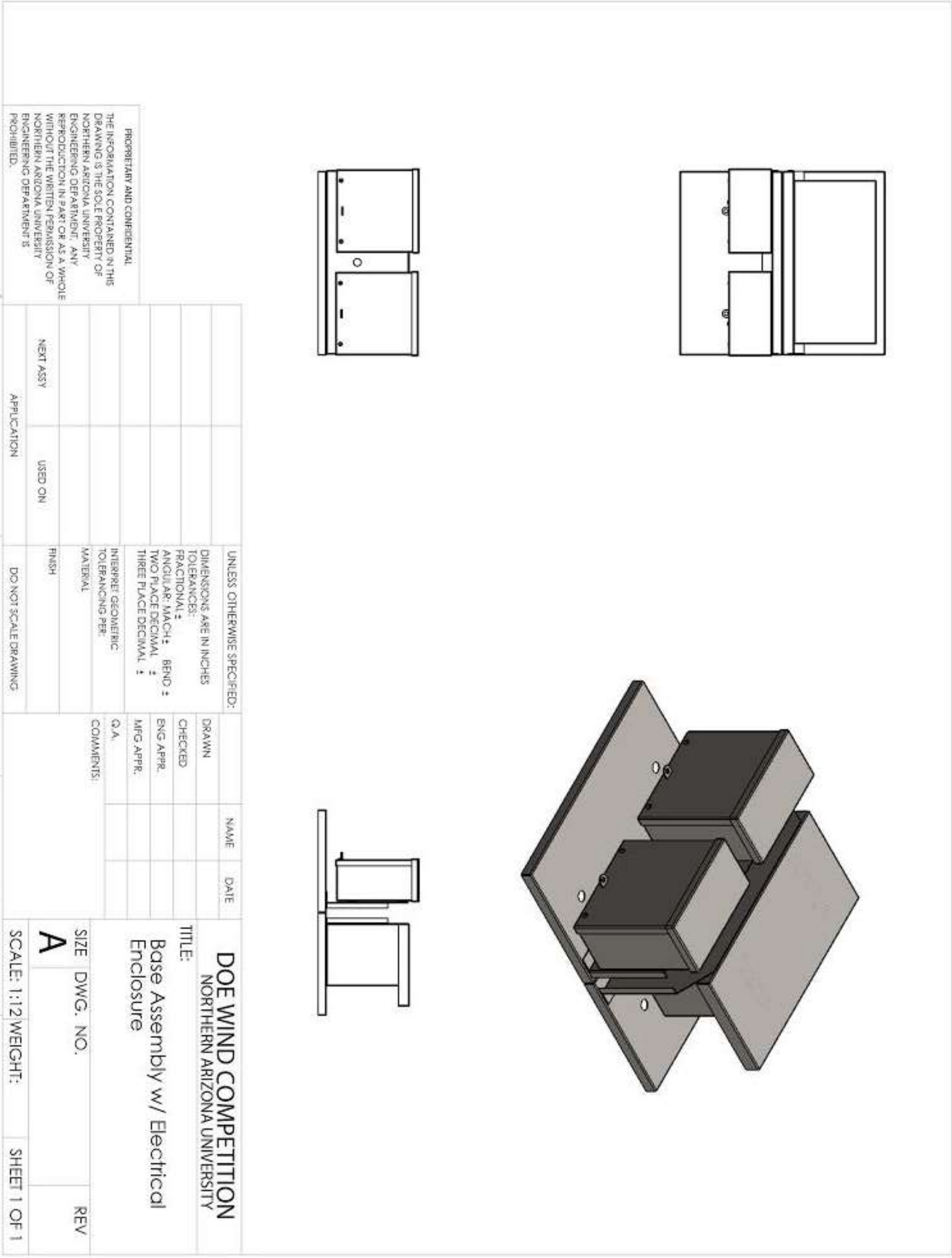


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Yaw Shaft	Fixed shaft which yawing system rotates about.	1
2	Yaw Bearing	Bearings fit to shaft and kept in place with spacers.	2
3	Bearing Spacer	Steel spacer holds bearings in place.	1
4	Small Bearing Spacer	Holds bearings in place.	1
5	Main Frame Yaw Plug	Press fit into Yaw Sleave and bolted to Main Frame.	1
6	Yaw Sleave	Steel sleave covers yaw shaft and is fit to bearings.	1
7	Tower Shaft Plug	Press fit into tower with threaded inner hole.	1
8	Slip Ring	Prevents wires from getting tangled as the system rotates	1

Mainframe Drawing



Base Drawling



Guy Wire Slip on Ring attachment Drawing